Additive Manufacturing Qualification Methodology for Spaceflight

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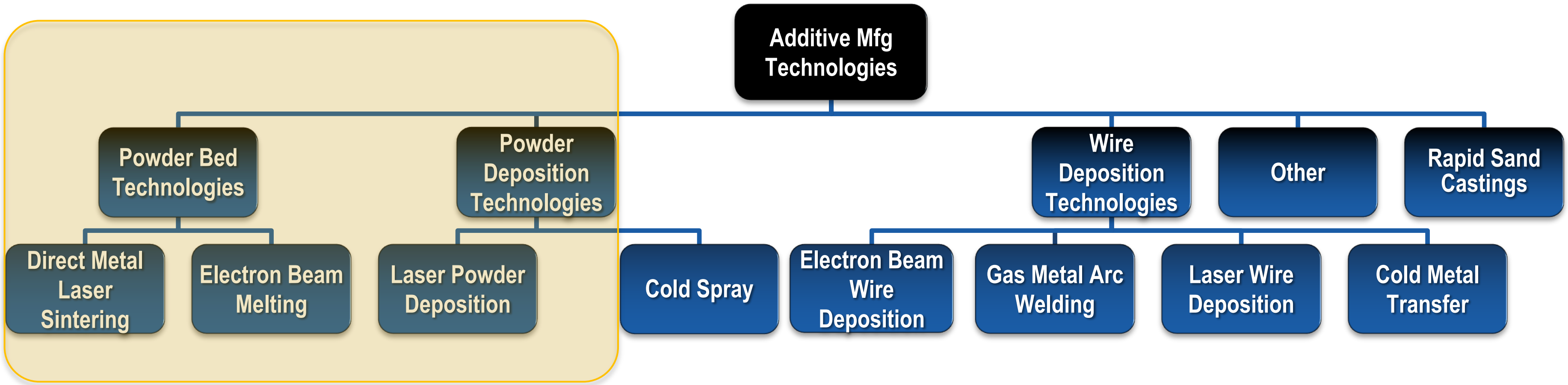
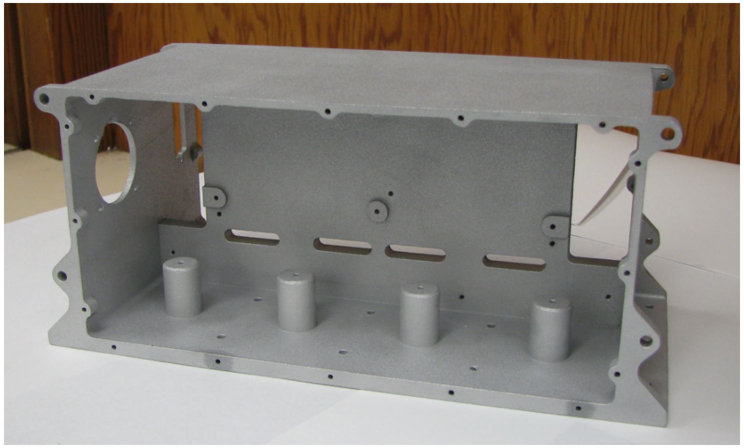
Agenda

1. Applications
2. Overview of AM at JPL
   - Processes
   - Machines
   - Materials
3. Flight Insertion & Qualification Opportunities
   - OCO-3/Ecostress
   - Gradients
4. Acknowledgements

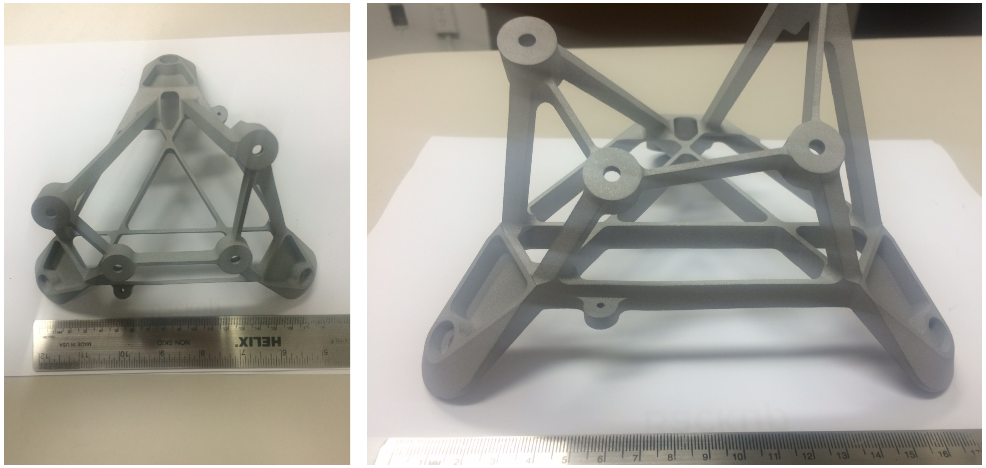
Additive Manufacturing Technologies Overview

Additive Manufacturing at JPL, briefing





Direct Metal Laser Sintering (DMLS)
SEP Electronics Chassis (AlSi10Mg)



Direct Metal Laser Sintering (DMLS)
MAHLI Bracket (AlSi10Mg)

Additive Manufacturing Materials, Metallics

Aluminum and titanium alloys comprise 85% of flight structural components

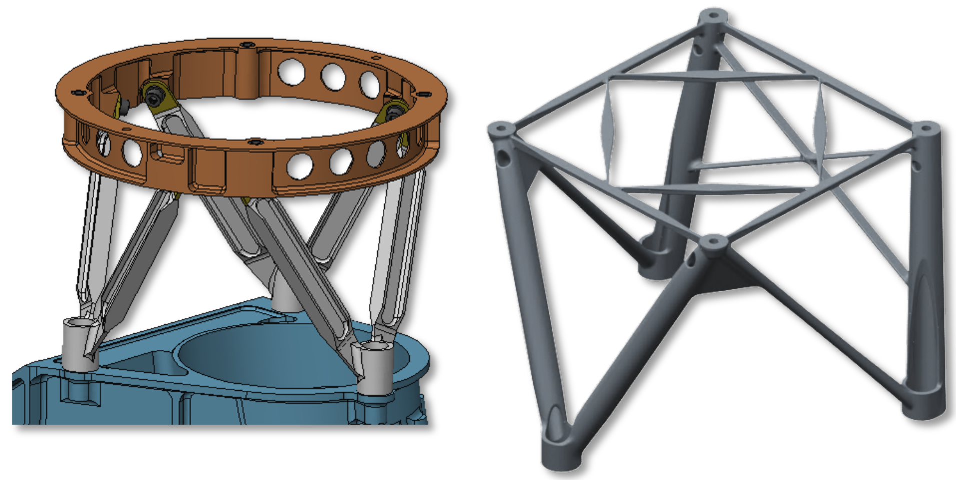
- Ti-6Al-4V produced via EBM (Arcam) process is baseline for flight use due to robust database
- JPL primary aluminum alloys are Al 2024, 6061, 7050, 7075
  - Current AM offering, AlSi10Mg (SAE 4032), doesn't correspond to existing alloy classes *used by JPL*
  - Challenge to integration due to lack of familiarity

Challenges

- Manned spaceflight and Class A missions require A-basis for primary structure, B-basis for secondary structure
  - Database for AlSi10Mg is not publicly available and is expensive for limited part set
- JPL's missions are generally single build, so total cost cannot be amortized over a single part or part-family

Qualification Methodology (Ti-6Al-4V)

- America Makes
  - B-Basis allowables effort current on-going to qualify Arcam electron beam melting machines (EBM)
  - Testing is a partnership between CalRAM (Camarillo, CA) and Northrop Grumman (El Segundo, CA)
  - ~ 1300 samples fabricated
  - Testing is currently on-going
- Additional testing
  - Test matrix is designed for generic properties; doesn't cover all of JPL's needs
  - Augmenting test matrix with specimens from CalRAM and testing JPL-specific conditions (e.g. – 100 ^{o}C fatigue/tension behaviors)

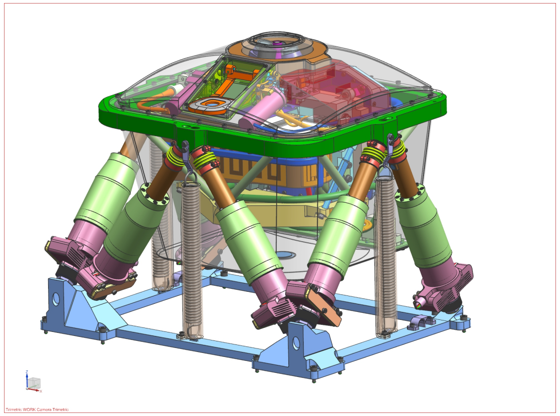


Mars Science Laboratory UHF Antenna Assembly

- Initial state (above left): 4-piece assembly with 6 bolted joints
- Final state (above right): 1-piece assembly
- 19% reduction in mass, as well as part count reduction

Qualification Methodology (AlSi10Mg)

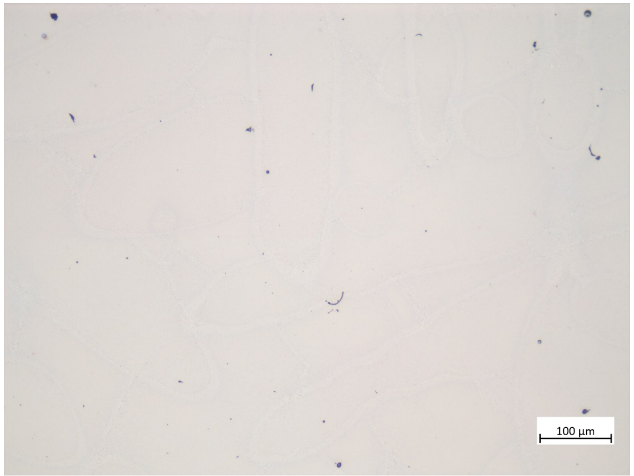
- Identification of insertion opportunities
  - Baseline properties determined through focused testing over a variety of temperatures (critical to JPL applications)
  - Capability determination of thermophysical properties
  - Testing is currently on-going
- Additional required efforts
  - Supplier variability
  - Aging
- Proof testing of components
  - Requires detailed understanding of actual loads and conditions
  - Must ensure testing accurately addresses concerns

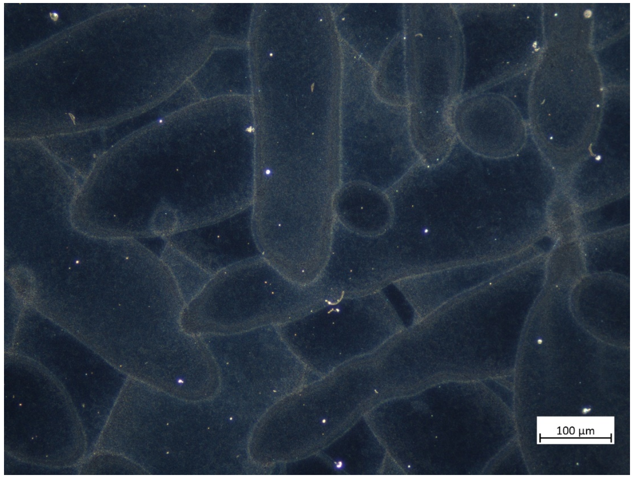


Planetary Instrument for X-ray Lithochemistry (PIXL), Mars 2020 (Image JPL/NASA)

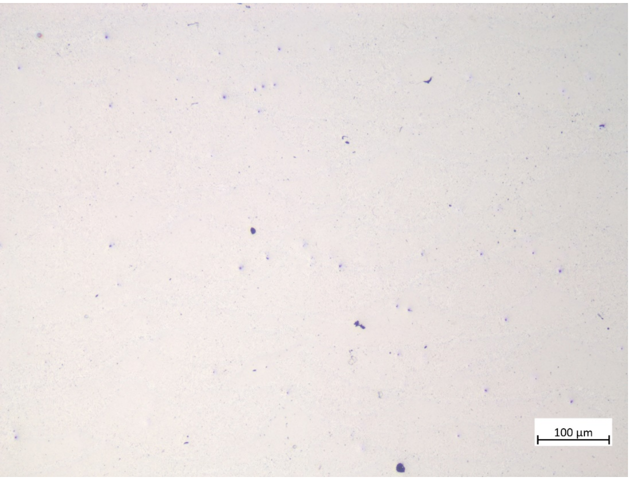
Element	Weight %
Al	Balance
Si	9.0-11.0
Mg	0.2-0.45
Fe	$\leq$ 0.55
Mn	$\leq$ 0.45
Ti	$\leq$ 0.15
Zn	$\leq$ 0.1
Cu, Ni, Pb, Sn	$\leq$ 0.05

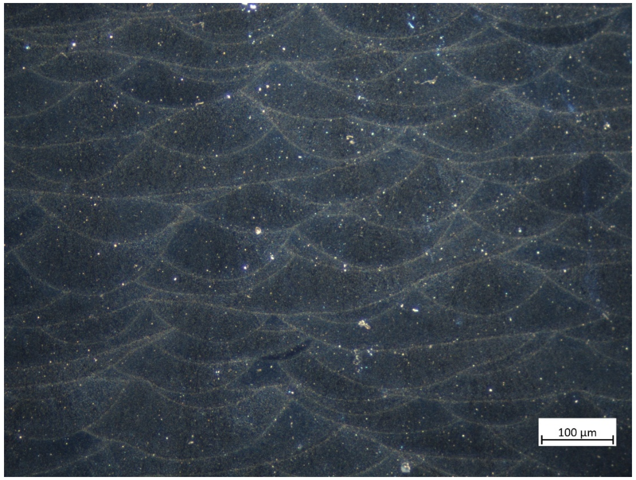
As-built microstructures





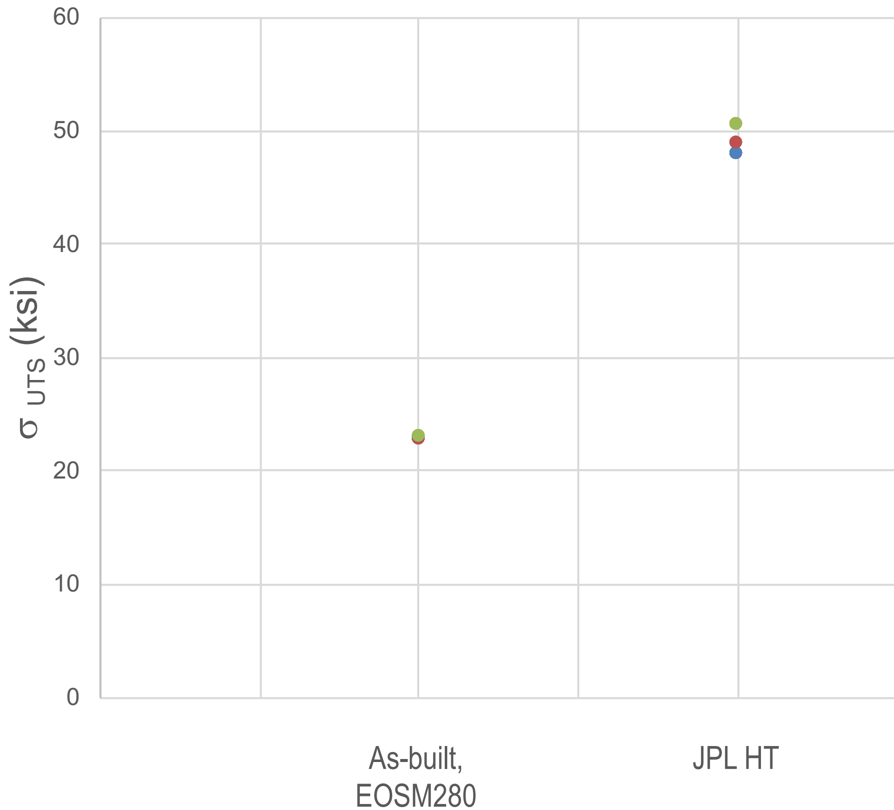
As-built, unetched, longitudinal (build) orientation; left: bright-field, right: dark-field





As-built, unetched, transverse orientation; left: bright-field, right: dark-field

Heat treatment effects



Standardized heat treatment
6 hrs at 538 °C (Ar)
Quench (H_2O) to 25 °C
158 °C, 2 – 4 hrs

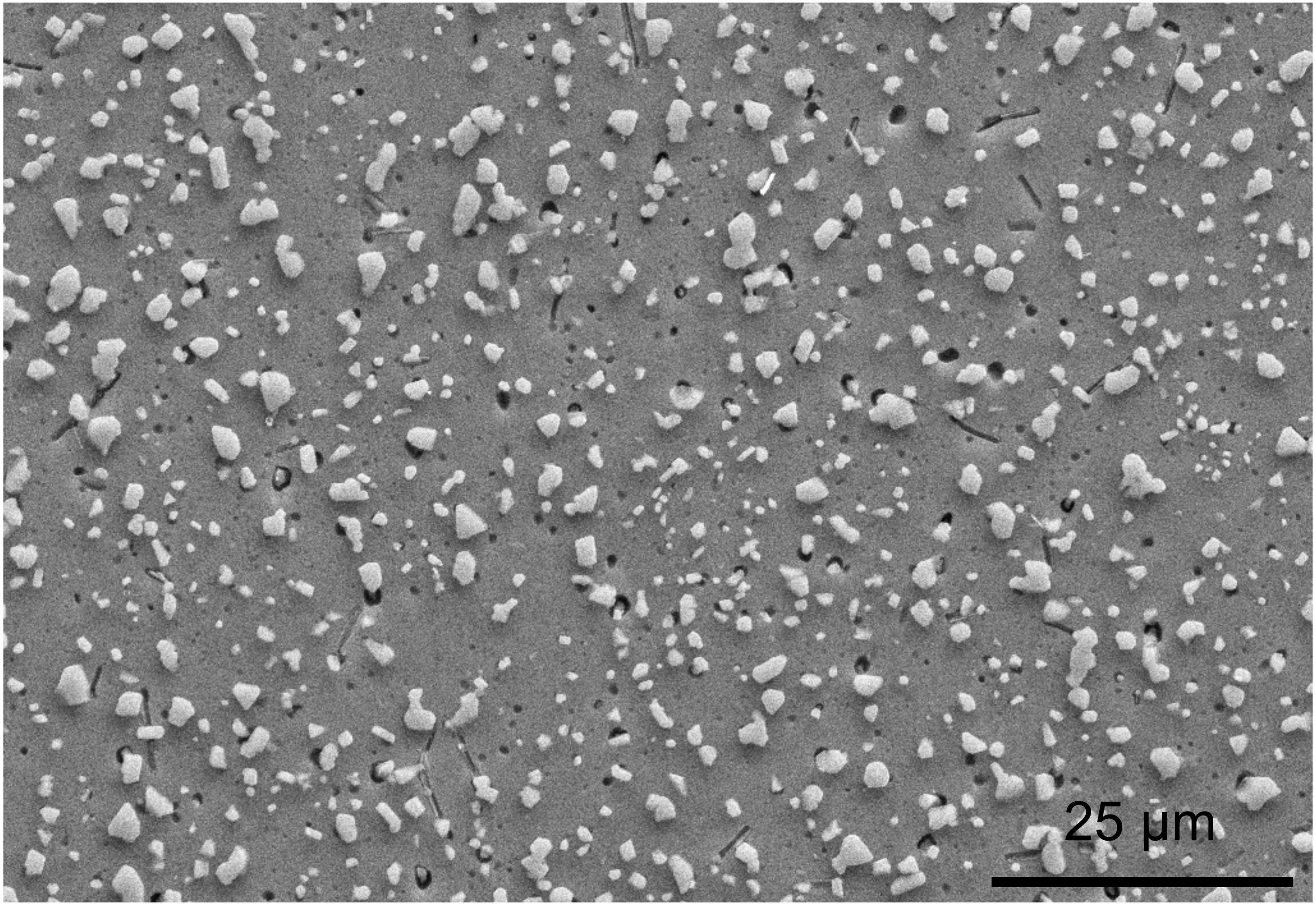
Elongation
As-HIP'ped: 30% ± 2.3%
Heat treated: 15% ± 1.4%

10 data points per condition

Instron 1331 #395182
Strain-controlled, 0.005 in/in/min
ASTM E8

Alexopoulos and Pantelakis, *Materials & Design*, **25** (2004) 419-430.
Rometsch and Schaffer, *Materials Science & Engineering A*, **A325** (2002) 424-434.

Heat treatment microstructure



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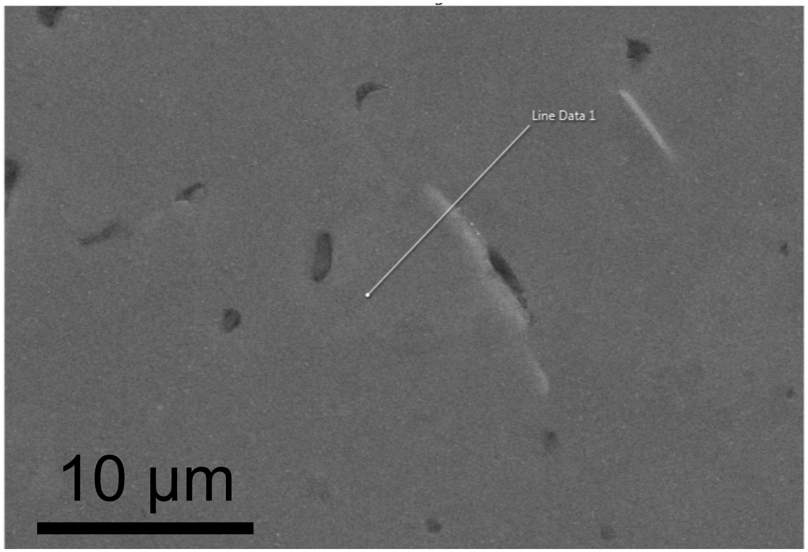
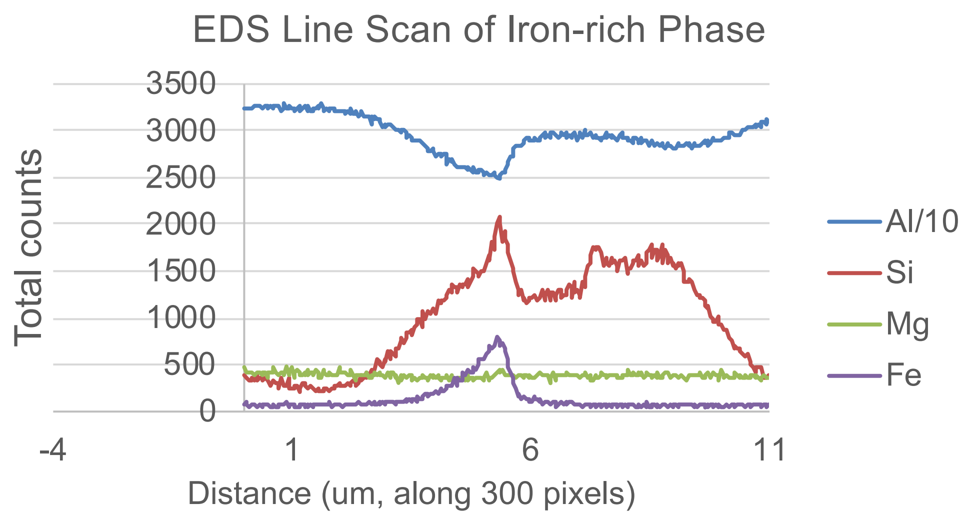
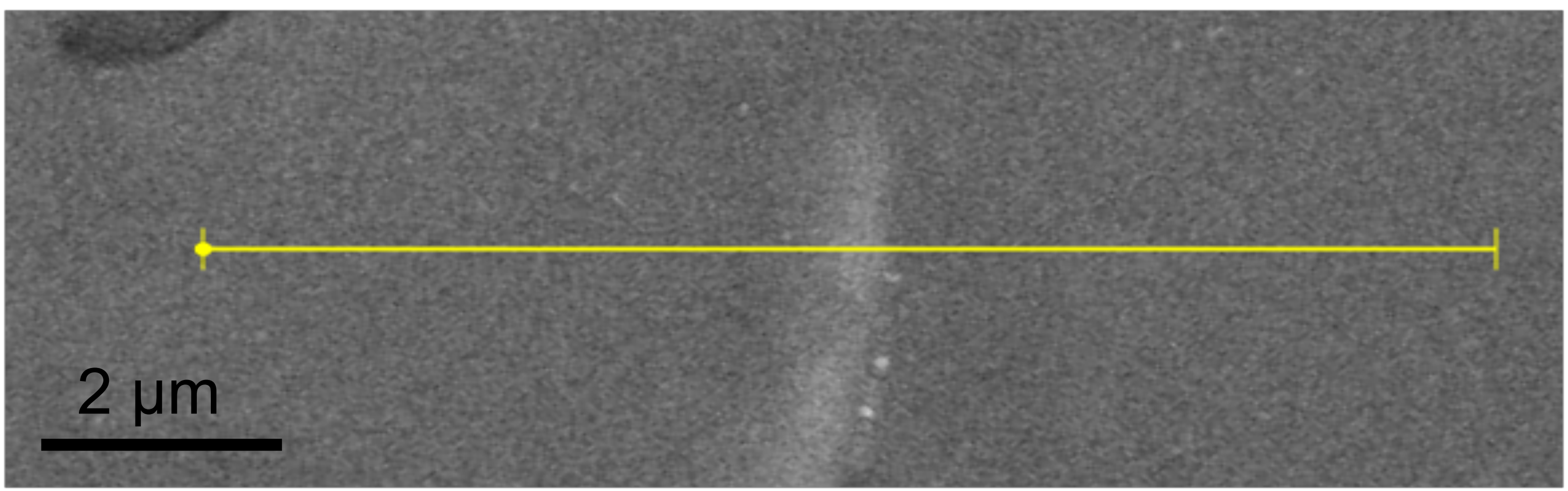
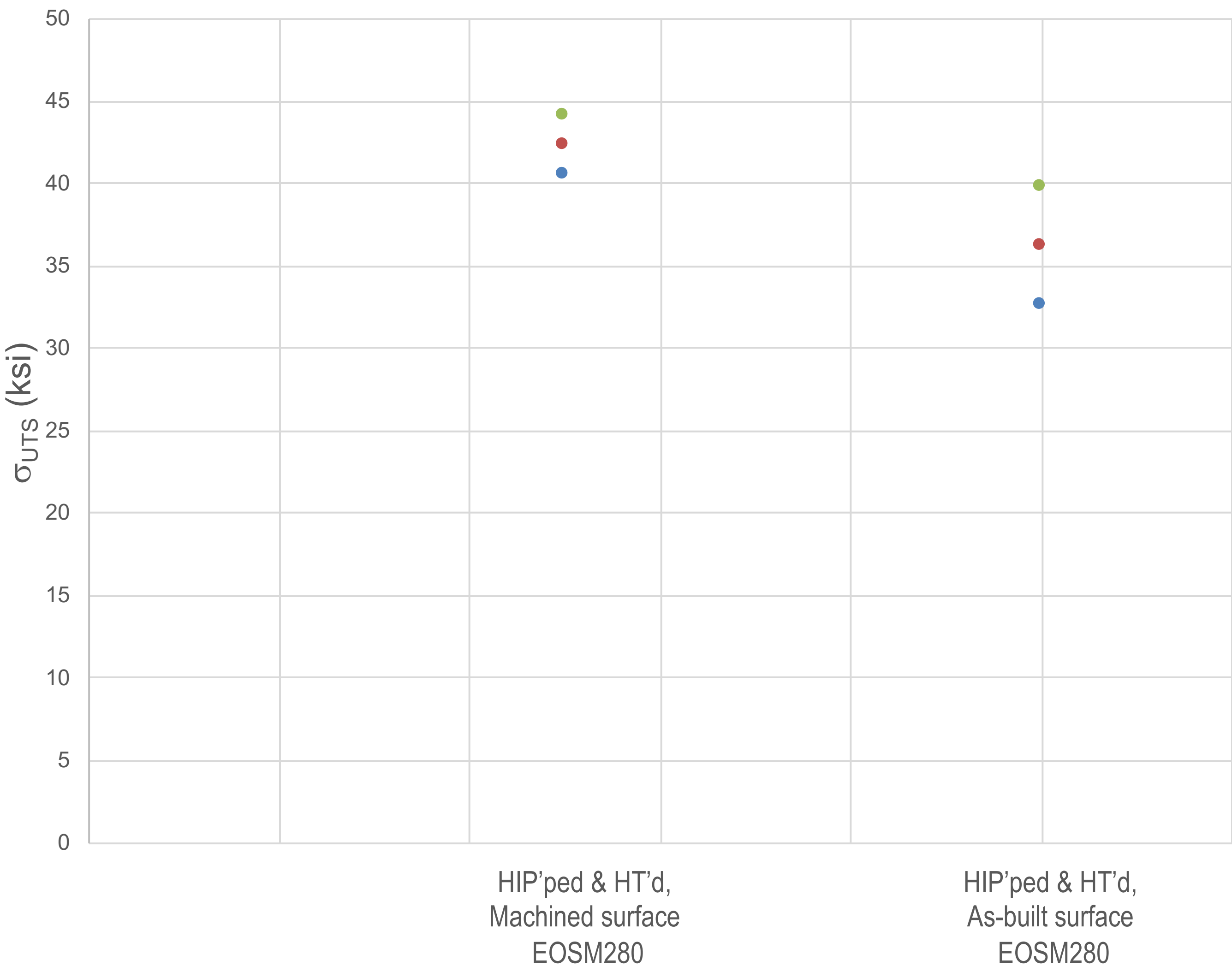




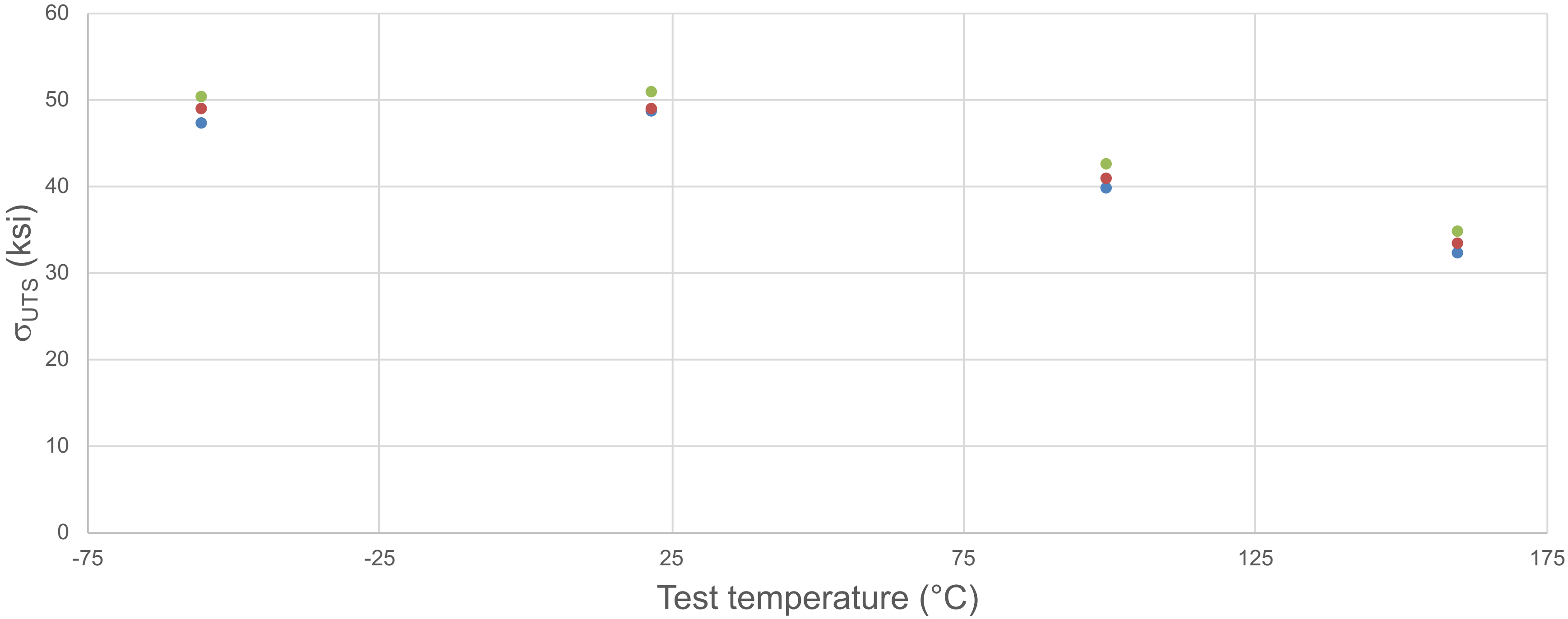


Surface finish effects



Instron 1331 #395182
Strain-controlled, 0.005 in/in/min
ASTM E8

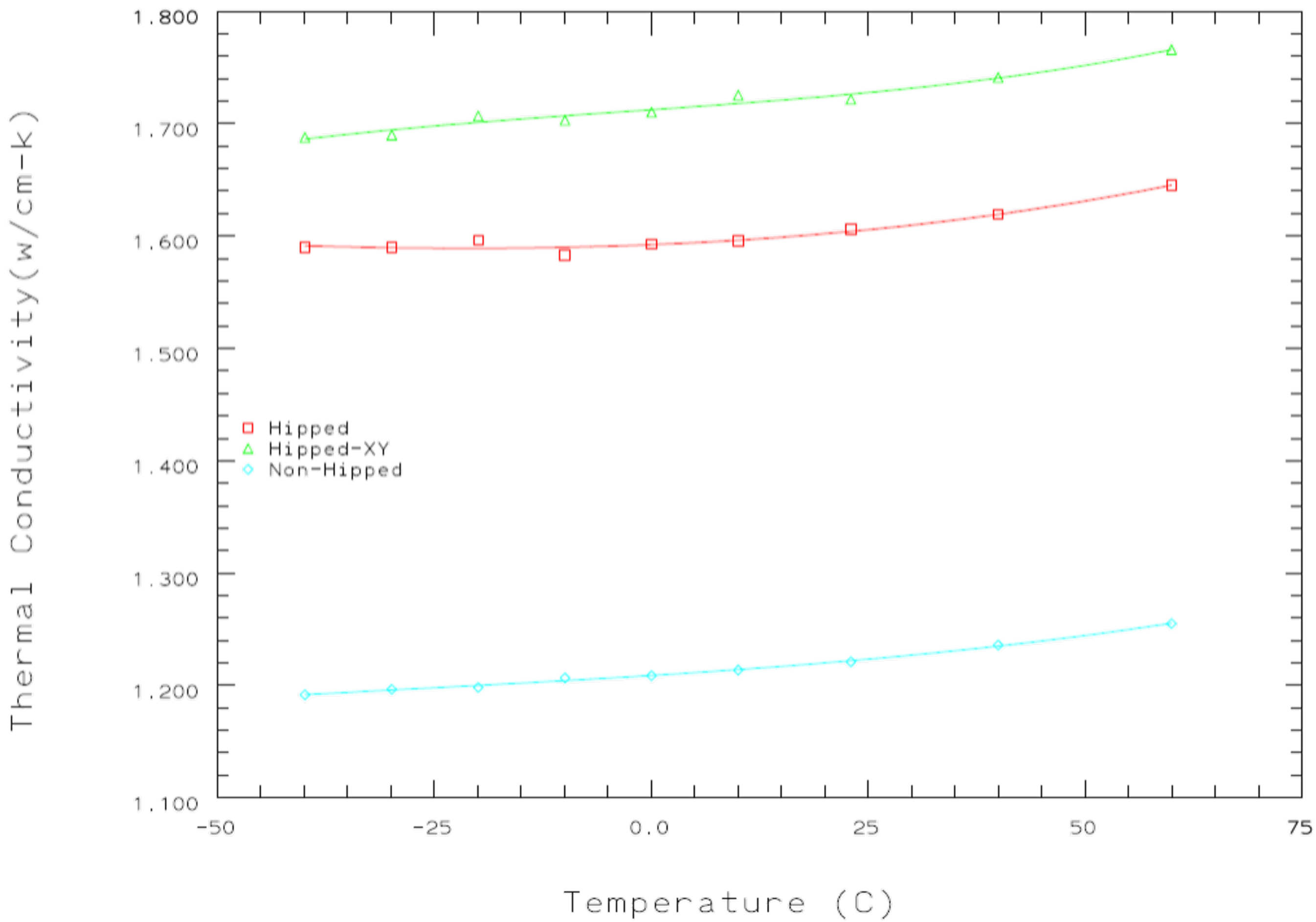
Tensile behavior of AlSi10Mg



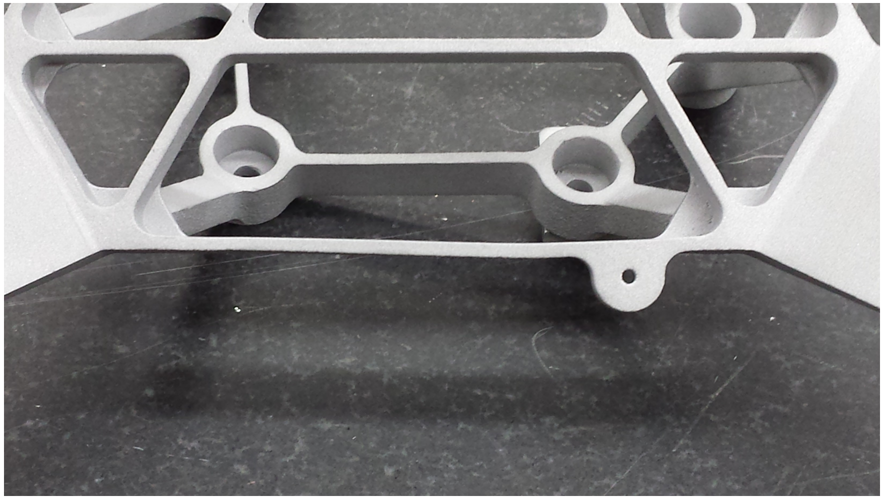
Testing performed with JPL standard heat treatment
Bemco thermal control chamber

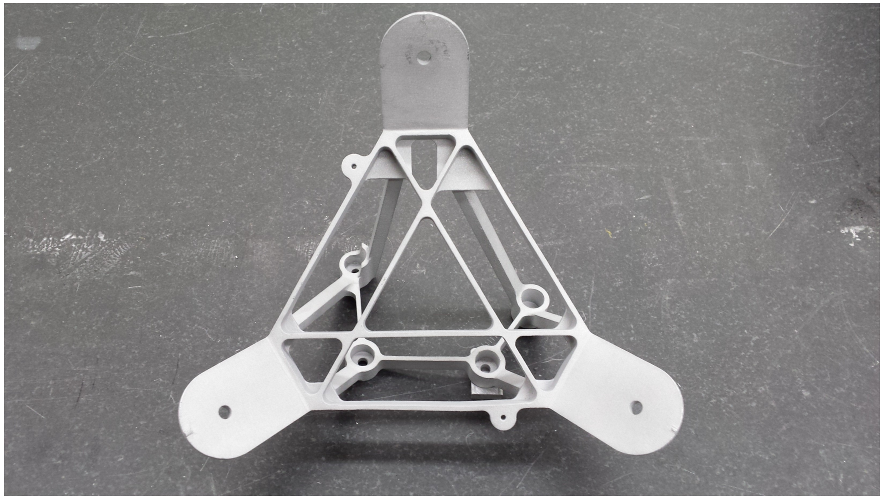
Instron 1331 #395182
Strain-controlled, 0.005 in/in/min
ASTM E8

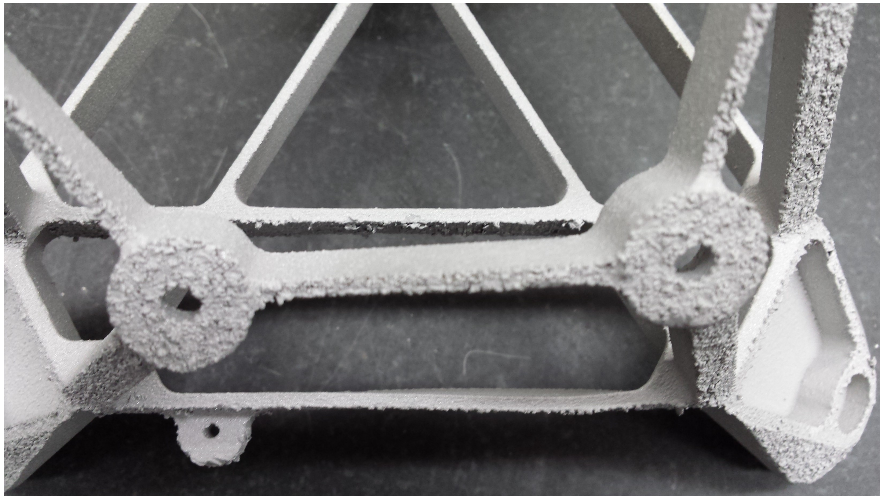
Additively Manufactured Aluminum Insertion (cont.)

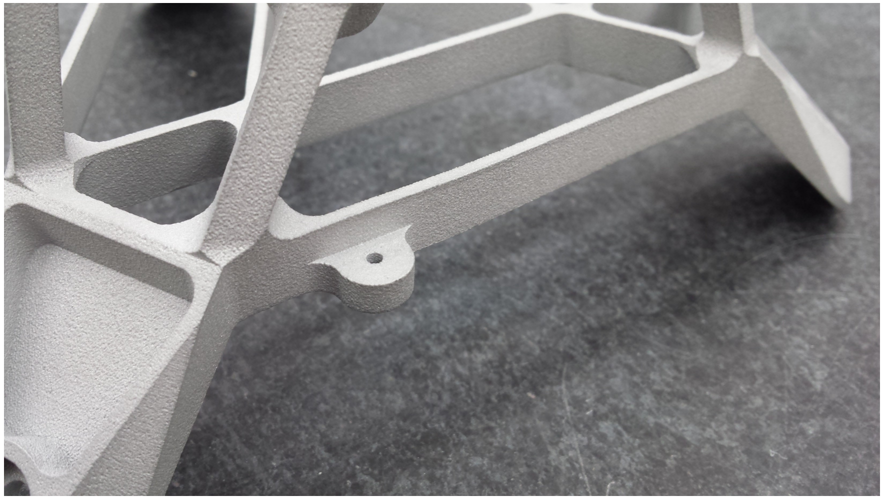


Vendor Comparison



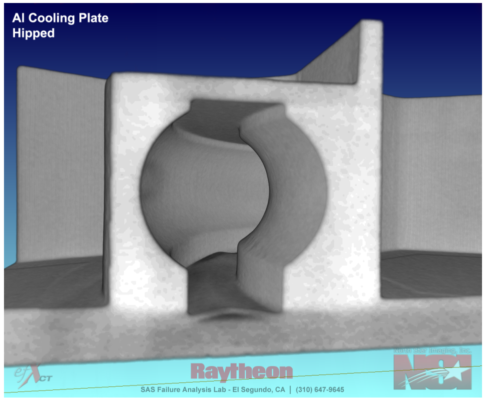


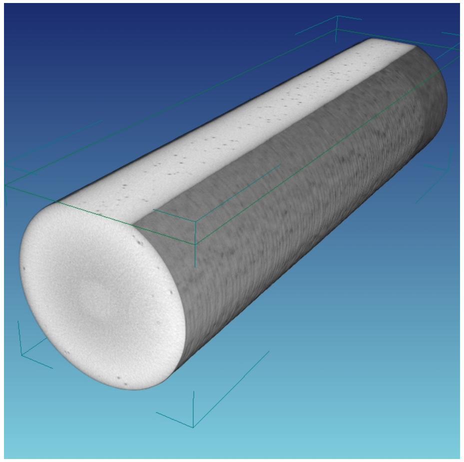


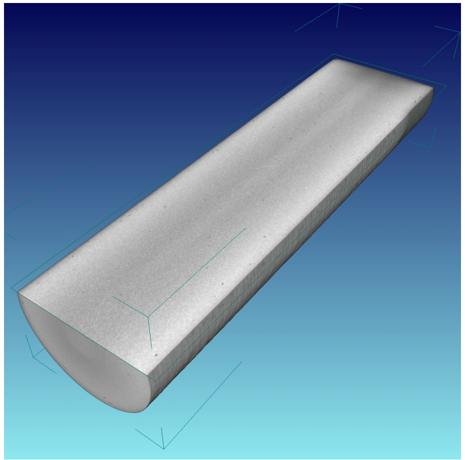


Non-destructive Evaluation (NDE)

1. CT inspection has not revealed when parameters aren't focused; with different parameters, flaws become evident (far right).
2. Larger defects (ultrasonic additive, left) apparent at different scales.
3. Building a series of samples with known flaws for evaluation with multiple techniques (e.g. CT, ultrasonic, etc.) to compare viability for inspection
4. Migration of porosity noted during HIP'ping.







Qualification Approach

1. **Organic development** of mechanical properties based upon program need.
    1. Require all projects to build standard geometry specimens and perform limited testing.
    2. Aim for common property needs (e.g. thermal conductivity, stress vs. strain, etc.)
    3. Programs requiring non-standard properties pay for testing (e.g. fatigue)
2. Focus on a **limited set** of alloys.
    1. AlSi10Mg is a potential replacement for some Al alloys
    2. Ti-6Al-4V can be utilized as a drop in (ELI version for specialty needs).
3. Materials & Processes focused on informed decisions for AM insertion onto flight programs.
    1. Avoiding improper usage (e.g. flat plate)
    2. Understanding complete process flow for post-build challenges (e.g. joining, surface finish, etc.)
    3. Understand nature of desired component

Acknowledgements

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